NIST Measurement Services: cw Laser Power and Energy Calibrations at NIST

NIST
Special
Publication
250-75

Joshua Hadler
Christopher L. Cromer
John H. Lehman

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[1]At Boulder, CO 80305
[2]Some elements at Boulder, CO

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Christopher L. Cromer
John H. Lehman

Optoelectronics Division
Electronics and Electrical Engineering Laboratory
National Institute of Standards and Technology
Boulder, CO 80305

July 2007

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National Institute of Standards and Technology Special Publication 250-75
Natl. Inst. Stand. Technol. Spec. Publ. 250-75, 32 pages (July 2007)
CODEN: NSPUE2

U.S. GOVERNMENT PRINTING OFFICE
WASHINGTON: 2007

For sale by the Superintendent of Documents, U.S. Government Printing Office, Washington, DC 20402-9325

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cw Laser Power and Energy Calibrations at NIST

Joshua A. Hadler, Christopher L. Cromer, and John H. Lehman
National Institute of Standards and Technology
325 Broadway
Boulder, Colorado 80305

This document describes a calibration service for absolute laser power and energy measurements of laser power meters and detectors used with continuous wave lasers at laser wavelengths between 325 nm and 1550 nm. In addition to a summary of the calibration procedure, a theoretical discussion of the uncertainty analysis and an overview of the measurement system are presented. A sample calibration report is included in this document that is similar to that provided to the customer. The calibration report contains an absolute calibration factor and a summary of the uncertainty assessment for the device under test.

Keywords: laser energy; laser metrology; laser power; optical detector calibration

1. Introduction

This calibration service provides absolute responsivity measurements for low power cw (continuous wave) laser power meters that are traceable to System Internationale (SI) units [1,2] through electrical standards. The service IDs for calibration services discussed in this document include 42110CA and 42111CA. High power cw calibration services (Power > 1 W) are discussed elsewhere [3].

2. Calibration Service Summary

In addition to a summary of the calibration procedure, a theoretical basis for the uncertainty assessment as well as an overview of the measurement system and operating procedures are given. A sample calibration report is included in this document that is similar to that provided to the customer. The calibration report supplies the customer with a correction factor (calibration factor) that is to be applied to the output of the customer's laser power meter.

The provision of calibration services (or measurement services in this document) is an essential element of the work of the Sources, Detectors, and Displays Group (as part of the Electronics and Electrical Engineering Laboratory) in fulfillment of its mission. In the conduct of this vital work, as in all its efforts, the group is committed to performance excellence characteristic of a global leader in measurements and standards. Our goal is to provide measurement services that meet the needs of our customers and, through continuous improvement, to anticipate their needs, exceed their expectations, and deliver outstanding value to the nation.

Within the ranges listed in Table 2.1 (see also Table 4 of the NIST Technology Service's General Information on Optical Radiation Measurements for Lasers and Optoelectronic Components Used with Lasers (currently available at http://ts.nist.gov/ts/htdocs/230/233/calibrations/optical-rad/laseroptoelectronic.htm), NIST can perform calibrations at the power (or energy) and wavelength specified by the customer. These ranges are determined by the combined limits of our standards and available laser sources. For these measurements, the customer's meter, or

device under test (DUT), is sent to NIST, where it is then compared to the appropriate laboratory *standard* using a calibrated beamsplitter measurement system.

The DUT may simply be a standalone detector, or it may be an integrated system with an independent display. Customers' meters are measured in the configuration that NIST receives. Detector/meter combinations are measured as a system and are not measured separately. Normally the response of the DUT is characterized, but no physical adjustments are made to the customer meter.

At the completion of the calibration measurements, the DUT and a calibration report are sent to the customer. The calibration report summarizes the results of the measurements and provides a list of the associated measurement uncertainties. The laboratory standards used as references for these measurements were designed and built at NIST. All of the critical parameters (electrical calibration coefficient, absorptivity, window transmittance, etc.) for the laboratory standards have been evaluated at the laser wavelengths and power levels for which they are used.

Table 2.1. Laser power and energy measurement capabilities.

Wavelength (nm)	Power range	Typical relative expanded uncertainty k=2 (%)
325	100 nW to 10 mW	1 to 2
488	1 nW to 1 W	0.5 to 1
514	1 nW to 2 W	0.5 to 1
532	1 nW to 20 mW	0.5 to 1
633	1 nW to 20 mW	0.5 to 1
830	1 nW to 20 mW	0.5 to 1
1064	1 nW to 2 W	0.5 to 1
1319	1 μW to 10 mW	0.5 to 1
1550	1 μW to 10 mW	0.5 to 1

More information can be found in NIST Optoelectronics Division Quality Manual (QM-II) for descriptions of NIST, the NIST Optoelectronics Division, and their quality systems.

3. Theory of Measurement

3.1 System Basics and Measurement Principle

The principal method used in this service is outlined by West, Case, Rasmussen and Schmidt [4]. This method, described as direct substitution, is the fundamental basis for the measurements provided by this service. While the types of devices that are measured may differ, and the procedures may vary, the fundamental method used in these measurements is essentially unchanged from the method described in the aforementioned publication.

Two calibrated detectors (standards) are used to calibrate the DUT by substitution of the DUT for one of the standards. A wedge beamsplitter is positioned to direct a reflected beam to one standard and the transmitted beam to a second standard. The optical properties of the wedge beamsplitter allow predictable attenuation control by multiple reflections from the beamsplitter. Utilizing different transmitted and/or reflected beams or by changing the beamsplitter material, different attenuation levels may be selected.

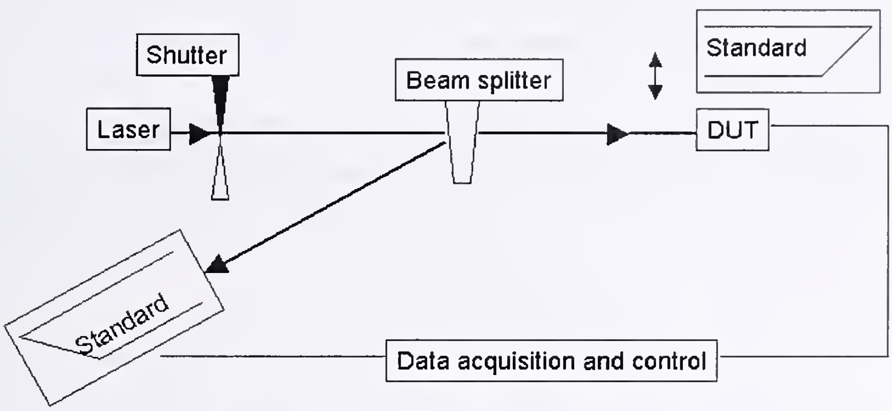

Figure 3.1. Beamsplitter/detector arrangement.

The beamsplitter ratio of the transmitted to the reflected beam power can be accurately determined by measuring both the transmitted and reflected beams simultaneously with the standards. By substituting the DUT for one of the standards, the DUT response can be observed with a known incident laser power. The other standard serves to monitor the power incident upon the DUT during the measurement. During the measurement of the DUT, this standard will be referred to as the *monitor*. This process is referred to as *Direct Substitution*, and is depicted above in Fig. 3.1.

3.2 Measurement Equations

For the purposes of discussing the general measurement theory of this service, we will be assuming an ideal detector having uniform response as a function of wavelength, position, temperature, etc. Specific issues such as uniformity, spectral response, linearity, and others will be discussed in more detail in the uncertainty section (Section 6) of this document.

For a detector with a measured output of X, responsivity of S, and incident laser power/energy of Φ, we can write

$$X = S \cdot \Phi . \tag{3.1}$$

X might be a voltage, current, or a numerical reading from an analog or digital meter. In practice, the calibration factor is determined by measurement of both the incident laser power (or energy) and the response of the detector. If the output is the raw voltage or current measured from the DUT, then the calibration factor is the responsivity of the detector. Otherwise, if the output is the observed reading from a meter, the calibration factor is to be applied to the meter readings to provide agreement between the DUT and NIST standards. This calibration factor, C, is given by

$$C = \frac{X}{\Phi}. \tag{3.2}$$

The value of the beamsplitter ratio can be determined by simultaneously measuring both the transmitted and reflected beams incident on the standard detectors. This gives us the beamsplitter ratio R in terms of the laser power measured by each standard.

$$R = \frac{\Phi_T}{\Phi_R}. \tag{3.3}$$

Once the beamsplitter ratio is determined, the calibration factor, C, of the DUT can be determined by substituting the DUT for either the transmitted side or reflected side standard. From Eqs. (3.2) and (3.3) we can express the calibration factors of the DUT in either case as

$$C_T = \frac{1}{R}\left[\frac{X}{\Phi_R}\right] \tag{3.4a}$$

or

$$C_R = R\left[\frac{X}{\Phi_T}\right]. \tag{3.4b}$$

In Eq. (3.4), the laser power or energy values are those measured during the measurement of the DUT. The value of the laser power or energy used during the measurement of the DUT can be significantly different from that used to determine the beamsplitter ratio, giving a much larger dynamic range available for calibrations. The materials selected for use as beamsplitters are chosen from known materials with linear optical properties. This allows for a much broader range of wavelengths and power levels to be utilized using the same beamsplitter.

3.3 Data Analysis

With the measurement principles outlined in section 3.2, we can discuss the actual data analysis used for the calibrations. In general, measurements of the DUT and standards are performed at discrete intervals in time. The shutter is used to turn the laser on and off during the measurements. During each measurement of the DUT, the dark (background) output is sampled with the shutter closed both before and after the measurement.

Beamsplitter ratio measurements are performed before and after the DUT measurements. The standards can be both power or energy type detectors and the beamsplitter ratio should be independent of the type of standard used.

Given the nature of the service, measurements are made across a wide range of power and energy levels and often with a combination of detector types. For the purpose of this discussion, we will look at the three basic analytical methods as they apply to the nature of the detectors and/or meters used in this service: power, energy, and calorimetery.

3.3.1 Power Meters

The process for calibration of a laser power meter begins by sampling the DUT background output before the shutter is open for a duration called the first *rating* period. This is followed by

a shutter-open period, during which the laser impinges on the DUT. Laser power meters generally have an output that reaches an equilibrium value some time after the shutter is opened, which is called the settling time.

The detector's settling time is derived from the thermal and electrical time constants, which are determined largely by the detection mechanism and related electronics, respectively [5]. In general, the settling time is the temporal difference between the instant of optical input and the time at which the detector has achieved steady state, and may be evaluated on a case by case basis. We typically define the settling time as seven times the dominant (longest) time constant of the detection system. Using this definition, the magnitude of the detector output will be at 99.9 % (as defined by $x \cdot e^{-7}$) of the theoretical maximum x. In Fig. 3.2, the settling time is shown graphically as the duration between the "shutter open" condition and the starting point of the "measurement period."

After the settling time, *n* number of readings of the DUT output are acquired and then averaged. The shutter is closed for another period while the DUT settles to the background level. A second set of samples of the background output is acquired from the DUT, which is called the second rating period. The interval between the shutter opening and shutter closing is referred to as the *injection* period. The signal from the DUT can then be calculated by subtracting the average background for both rating periods from the average DUT output with the laser on. If the DUT has an analog or digital display, then visual readings may be recorded by the operator during this process.

The standard is used to measure the laser power incident on the DUT during the measurement. If the standard is an energy type of detector, then the injection period is used to calculate the average power during the measurement.

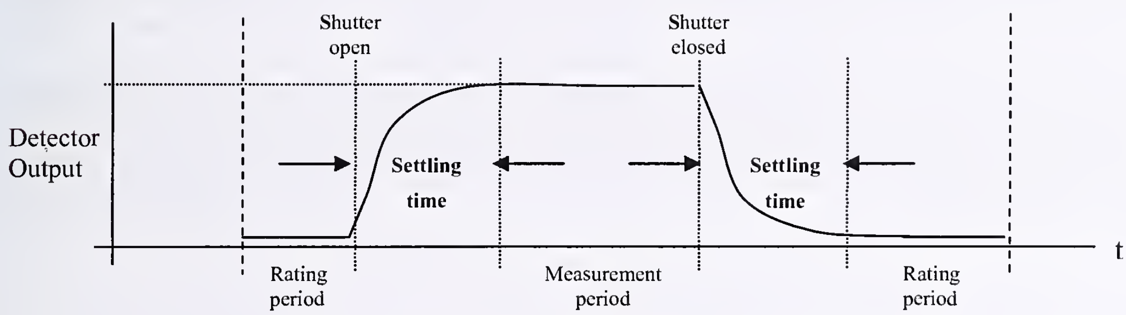

Figure 3.2. Example of laser power detector output vs. time.

3.3.2 Energy Meter

The sequence of events for measurement of energy meters is fundamentally the same as that of power meter measurements, although the data analysis may vary. There are many types of energy meters that might require calibration. Some may have an output that is similar to that in Fig. 3.2, but the analysis may be performed differently, depending on the specifics of the DUT. The baseline is still determined from the rating periods before and after the injection period. The average baseline is subtracted first from the entire waveform. The waveform is then numerically

integrated from the data acquired during the period defined by the opening of the shutter to the end of the settling time after the shutter is closed. Other types of energy meters may require a measurement of the peak output from the DUT as the output to use in the calibration. If the DUT has an analog or digital meter, then visual readings may be recorded by the operator during this process.

For energy meter calibrations, the standard used will determine the total energy incident on the DUT during the measurement. If the standard is a power meter, then the integrated power from the standard must be used along with the total shutter open period to determine the total laser energy incident on the DUT.

3.3.3 Calorimeter (Energy) Meter

Laser calorimeters are a special type of energy meter described by E.D. West and K.L. Churney in *Theory of Isoperibol Calorimetry for Laser Power and Energy Measurements* [6]. Calorimeter theory is a mature field, and the discussion by West and Churney still forms the basis of current calorimeter measurement theory. A waveform in the figure below is typical of the raw output of a laser calorimeter.

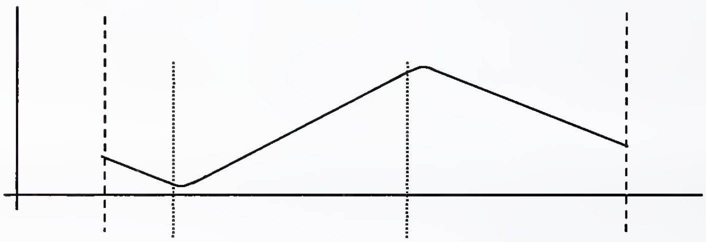

Figure 3.3. Example of calorimeter output versus time.

Measurements performed with a calorimeter incorporate the pre- and post-rating periods (before and after the shutter). The mathematical treatment of the signal from a calorimeter, also known as the corrected rise equation, which is used to define the temperature measured in the calorimeter and correct for the heat exchange internal to the calorimeter during the measurement period, is described in detail by West and Churney [6]. The analysis of the response of this detector is still that of an energy meter, and the measurement method used is similar to that described in section 3.3.2.

4. Measurement System

4.1 Measurement Standards

Energy and power measurements can be acquired using a variety of types of detectors. Such detectors might include, but are not limited to, thermopiles (surface and volume absorbers), calorimeters, and diode-based detectors (including multi-diode trap and tunnel configurations). More than one type of detector or standard may be employed as a transfer standard for any given measurement. NIST Standards currently in use for this service include the C-Series Laser Calorimeters [4,6,7,8], and NIST Standard Diode Trap Detectors [9,10,11,12,13,14,15].

Historically, calibration services for laser power and energy meters have been provided by use of calorimeters that were electrically calibrated and directly traceable to SI units through electrical standards. Presently this traceability is established by comparison with the NIST Laser Optimized Cryogenic Radiometer (LOCR) [16,17] which in turn is traceable to electrical standards.

Power measurements are made by recording and averaging the peak signal generated after the detector output has come to a steady state while the beam is incident on the detector. Energy measurements require a different mathematical treatment of the same signal. That is, with knowledge of the injection time, the output signal is integrated over time to quantify a measurement of energy rather than power.

Calorimetry is inherently a measurement of thermal energy, but may also be used to determine average power as well. The analytical methods of calorimetry differ from those used with thermopiles, photodiodes, and pyroelectric-based optical detectors, although the measurement periods are the same.

All of the standards used in this measurement service have been calibrated with the NIST Laser Optimized Cryogenic Radiometer [7,15,16,17].

All data and characterizations of these standards can be found in the 42110CA service quality manual.

4.2 Laser Sources

The 42110CA and 42111CA calibration services rely on a suite of commercial laser sources, capable of a broad range in both power and wavelength, extending from the near-UV to the mid-IR at power levels up to 1 W.

4.3 Optical Setup

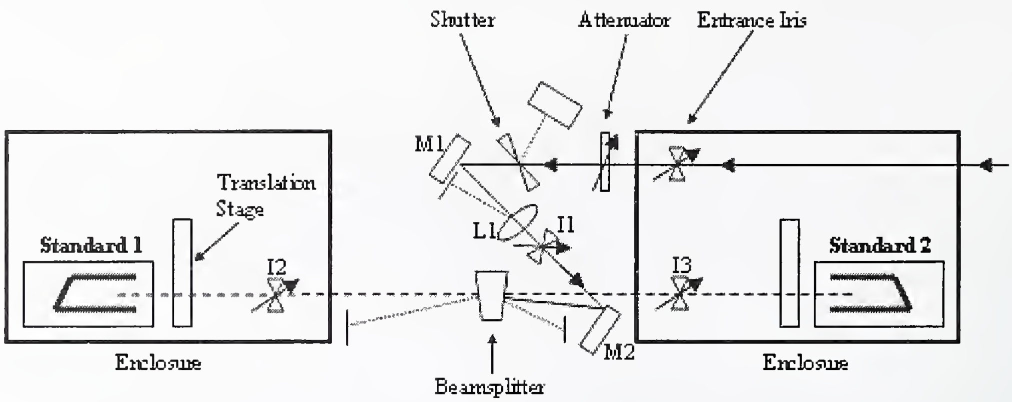

Figure 4.3. Example optical layout.

The basic optical setup is represented here in Fig. 4.3.

4.3.1 Attenuator

An attenuation system is used for control of the laser power delivered to the measurement system. As defined previously in section 3.2, the laser power level used for calibrating the beamsplitter ratio need not be the same as that used for measurement of the DUT. Thus, a method of adjusting beam power is used that will not impart steering effects or otherwise change the overall beam profile. The method of attenuation may change depending on the laser source and the power levels desired. These methods may employ neutral density filters, low transmittance mirrors, or polarization-based techniques.

4.3.2 Shutter

It is necessary to control and quantify the injection time during a measurement. A computer-controlled shutter is used. The data acquisition system controls this shutter remotely and records the duration of the shutter opening.

4.3.3 Mirrors and Focusing

The nature of the suite of laser sources, and the diversity in the type and size of a test detector, require a flexible optical layout. Multiple mirror sets are maintained, each set allowing for optimum transmission in a particular wavelength band. Additionally, a wide array of lenses is utilized to allow for a large range of beam profile sizes incident on the detectors. A schematic of a typical optical layout is shown in Fig. 4.3.

4.3.4 Beamsplitters

A selection of beamsplitters is used to accommodate different wavelengths. Because the beamsplitter ratio and efficiency are wavelength dependent, the beamsplitter ratio must be determined at each wavelength for which the beamsplitter is employed.

Intersecting each beam path, transmitted and reflected, from the beamsplitter is an enclosure. The detectors in use (standards and DUT) are placed in the enclosures (depicted in Fig. 4.3) to reduce the amount of stray light contributing to the measurement and to buffer temperature changes the

measurement lab may experience. Each enclosure contains its own precision measurement electronics to avoid unnecessarily long signal path lengths to the data acquisition electronics. These meters are then read remotely via computer into the data acquisition system.

4.4 Data Acquisition

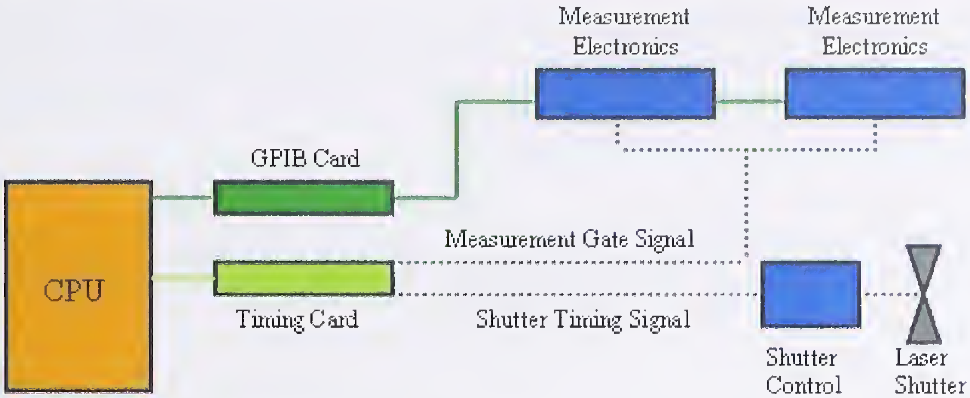

Figure 4.4. Block diagram of data acquisition system.

The basic data acquisition system is depicted in Fig. 4.4 above. Data acquisition and analysis are automated by means of a desktop computer and customized software. Remote communication with the instruments in each detector enclosure allows a single computer to monitor both instruments (in the transmitted and reflected beam paths) simultaneously.

The software allows for independent control of injection time, background measurement, and correction. Data analysis is performed real-time and is intended to allow for user interaction as a time-saving measure. The types of detectors (energy, power, or calorimeter) are selected by the user, and other static elements such as wavelength, beam and environmental conditions can all be entered into the main program. The injection and background, rating, and cooling times are also user controlled and set.

The software will collect data for the initial beamsplitter measurement *n* times (set by the user). The subsequent DUT measurement will then be taken and the beamsplitter ratio be used to calculate the beam power incident on the DUT, based on the second standard's output. This measurement will also run for N cycles, which is set by the user. Following the DUT measurement, a second set of beamsplitter measurements is taken to assure that there has been no significant drift in the beamsplitter ratio.

5. Standard Operating Procedures

5.1 System Startup

All electronics and other support systems are powered up at least one hour prior to the start of the measurement. All test equipment is allowed to equilibrate with room temperature. The laser is selected for the desired wavelength and power, and is energized at least one hour before alignment to allow for stabilization of the laser pointing.

5.2 Optical Alignment

The alignment of the laser beam is critical to ensure a reliable measurement. Adjustable apertures are set to block stray light (scatter and halo), but not occlude the beam incident on the DUT and/or standard(s). The beam is centered on the DUT.

5.2.1 Beam Extent

The diameter of the extent of the beam must be smaller than the active areas of the DUT and standards involved. The extent of the beam is defined by the diameter where 99.9 % of the beam power is contained. The extent of the beam is determined by placing a centered adjustable aperture in front of a power detector (placed at the same relative position as the DUT), with the aperture is set to occlude 0.1 % of the incident beam. The diameter of the aperture at this point establishes the extent of the beam. This diameter should generally be less than half the active area of the DUT.

5.2.2 Beam Size

Beam size is generally considered to be full-width at half-maximum of a Gaussian distribution. For the purposes of this measurement, an approximation of 1/e times the beam extent is used to determine the beam size. Additionally, if the customer specifies a specific beam size, the optics are set accordingly.

5.2.3 Beam Alignment

The alignment process follows these basic steps:

1. Select the proper optics for the measurement. This includes, but may not be limited to, mirrors, lenses, filters, and/or attenuators.
2. Ensure that the beam is centered through attenuator and centered on the shutter.
3. Direct the beam to both detector enclosures by steering mirrors M1 and M2, shown in Fig. 4.3
4. Place focusing lens L1 to the necessary position to establish proper beam size, and align lens so the beam is centered and normal to the surface of the lens. Normal incidence may be determined by observing the retro-reflection from the lens, and centering the retro-reflection on the upstream mirror.
5. Steer the focused beam to the center of the alignment target in each measurement enclosure.

6. Set adjustable apertures in the beam paths to block scattered light and stray beams, but not so as to occlude the measured beam.

5.3 DUT Alignment

The DUT is mounted on a translation stage such that it can be easily inserted and removed from the incident beam. The DUT is then positioned so that the beam is centered on the DUT. Perpendicularity can be set on detectors that produce a specular reflection by steering the retro-reflection off the DUT so it is coincident with the incident beam.

5.4 Data Acquisition

The data acquisition of this measurement service employs computer-controlled remote measurement equipment. The software that controls the measurement also analyzes the collected data. Data collection is performed in three separate intervals.

1. Beamsplitter measurements are taken. Multiple samples are acquired. The number of samples may vary depending on injection time and detectors used.
2. DUT measurements are taken. Again, the number of samples may vary depending on detectors and injection times.
3. A second set of beamsplitter measurements is taken. This is to ensure that the beamsplitter ratio has not changed during the test meter measurement.

Analysis of the data occurs after each measurement.

5.4.1 Software Setup

Before measurements begin, all of the necessary information must be entered the data acquisition software.

The first information to be entered is the general information about the overall measurement.

1. Wavelength to be measured: This allows the system to compensate for any wavelength dependencies that may be inherent to a given standard. For calorimeters, this can be window transmittance, which can vary with wavelength. For diode-based detectors, this will call up data stored on the system regarding the responsivity (A/W) at a given wavelength of the standard being used.
2. Temperature and humidity.
3. Calibration service specific information, NIST ID number and NIST folder number.
4. Any other general information; including, but not limited to, DUT name, customer, power level measured, unique optics used (focusing lenses, for example).

Next, information specific to the beamsplitter measurements is entered:

1. Detectors/standards used: Both detectors (transmitted and reflected) are identified and selected in the software interface.
2. Type of detector: power, energy, or calorimetric.
3. Electronics settings that are enabled for remote control: gain ranges for remote voltage and/or current meters are set; in addition, specific channel allocations on multiplexed meters are set.
4. Time constant of detectors used.

5. Standard/monitor gain.
6. Background, or rating period.
7. Injection time.
8. Settling time (usually 7 × time constant). The settling time is generally established by the manufacturer's specification. Where the settling time is less than that of the NIST standard being used, the settling time of the NIST standard takes precedence.
9. Duration/period for each data point recorded.

Similarly, this information is set for the DUT measurement. Detector-specific information for the monitor detector should not be changed from that defined during the beamsplitter measurement. Rating period, injection, settling, and time intervals are to be set according to the needs of the calibration and may differ from those used for/in the beamsplitter measurements.

5.4.2 Software Operation

During software operation, the beamsplitter measurements are started, and the number of measurements (N) and the cooling time between each measurement are set. Cooling time is set when utilizing any type of thermal detector in the measurement process. The purpose is to allow the detector output to drop as the detector itself cools. This value is variable and depends on the amount of energy injected and the desired starting value, where applicable. When the beamsplitter measurements are completed, the test-meter measurements are launched. The number of measurements (N) and cooling time are also entered during this operation. Additionally, the option for "visual" recording is selected and controlled. Often, laser power meters will have no remote measurement output (such as remote computer read back or analog output) and measurements will rely on visually recording the meter reading from the display of the test meter itself. The software allows for entering this information for each measurement in the set of measurements for the test meter.

5.5 Data Analysis

Most of the pertinent analysis is performed in real-time during the measurement by the software.

1. Power and/or energy levels of both transmitted and reflected beams during the beamsplitter measurements are calculated. Selection of the detector and detector type determines what algorithms the software will use in analysis.
2. From these power/energy measurements, the beamsplitter ratio is determined, and standard deviation is calculated. Selection of gain and range in the software settings scales the measurement to the instrument's gain, and yields the true power measured.
3. Power and/or energy levels of both transmitted and reflected beams during the DUT measurements are calculated.
4. From these power/energy levels, the calibration factor for the DUT is determined, and standard deviation is calculated.

Following the measurement, the uncertainty contributions are determined depending on the detector(s) employed in the measurement, and the total uncertainty is calculated.

Performance of the software operation is validated semiannually through intercomparison calibrations with other Calibration Services in the CW Laser Radiometry Project [15].

6. Uncertainty Evaluation

The uncertainty estimates for the NIST laser power and energy measurements are assessed following guidelines given in NIST Technical Note 1297, "Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurement Results" by Barry N. Taylor and Chris E. Kuyatt, 1994 Edition [18]. To establish the uncertainty limits, the error sources are separated into (1) Type B errors, whose magnitudes are determined by subjective judgment or other non-statistical method, and (2) Type A errors, whose magnitudes are obtained statistically from a series of measurements.

All the Type B error components are assumed to be independent and have rectangular or uniform distributions (that is, each has an equal probability of being within the region, $\pm\delta_i$, and zero probability of being outside that region). If the distribution is rectangular, the standard deviation, σ_s, for each Type B error component is equal to $\delta_i/3^{1/2}$, and the total *standard uncertainty* is $(\Sigma\sigma_s^2)^{1/2}$, where the summation is performed over all Type B error components.

The Type A errors are assumed to be independent and normally distributed, and consequently the standard deviation, S_r, for each component is

$$S_r = \sqrt{\frac{\Sigma x^2 - \frac{(\Sigma x)^2}{N}}{N-1}} ,$$

where the *x* values represent the individual measurements and N is the number of *x* values used for a particular Type A error component. The standard deviation of the mean is $S_r/N^{1/2}$, and the total *standard uncertainty* of the mean is $[\Sigma(S_r^2/N)]^{1/2}$, where the summation is carried out for all the Type A error components.

The *expanded uncertainty* is determined by combining the Type A and Type B "standard uncertainties" in quadrature (the *combined uncertainty*) and multiplying this result by an expansion factor of 2.

The expanded uncertainty, U, is then

$$U = 2\sqrt{\Sigma\sigma_s^2 + \Sigma\frac{S_r^2}{N}} .$$

The number of decimal places used in reporting the mean value of the calibration factor listed in the calibration report is determined by expressing the expanded uncertainty to two significant digits.

6.1 Measurement Standard Uncertainties

The uncertainties specific to any given reference standard are documented in the C-series Calibration Services Quality Manual III (QMIII) specific to the 42110CA and 42111CA calibration services. However, it is proper to discuss the nature of these types of uncertainties, and their contribution to the overall uncertainty evaluation for each standard. Not all of the following uncertainty contributions will apply to any given standard, and in some cases, only a few will be applicable. An example error budget is summarized below in table 6.1.

6.1.1 Spectral Responsivity (Type B)

Spectral responsivity is generally defined as output per incident power and/or energy. It is expressed most often as responsivity at a specific wavelength, most notably for diode-based detectors, which can have large variations of responsivity at different wavelengths. This contribution is determined by measurements performed by either the Spectral Responsivity Measurement Service [19], by comparison with Laser Optimized Cryogenic Radiometer [16] measurements.

6.1.2 Absorbtivity (Type B)

The absorptivity of thermal-based detectors tends to have a uniform spectral responsivity, but the uncertainty in the actual absorptivity value is still essential to account for in the error summary for each detector. The uncertainty associated with the absorbtivity of the standard calorimeters used in this service is discussed by T.R. Scott [8].

6.1.3 Uniformity (Type B)

The beam position incident upon the detector during any given measurement is highly repeatable. However, the absorptivity, or responsivity, of the detector may vary as a function of location or position over the active surface. This contribution is generally determined by sampling the detector response over a two dimensional array over the active detector area, as described by the Spectral Responsivity Measurement Service [19]. The uncertainty contribution depends on uniformity variations of the detector and the beam size during the measurement of the uniformity.

6.1.4 Polarization Dependence (Type B)

Laser light is often strongly polarized. Some detectors, especially diode-based detectors, may respond differently depending on the polarization state of the incoming light. For these detectors, this polarization dependence must be known and quantified if necessary. Examples of detectors that are insensitive to polarization are surface absorbing thermopiles and pyroelectric detectors. The polarization state of the incident laser is determined by the laser itself and any polarizing optics that are in the beam path. The polarization dependence of the detector is characterized by a change in the responsivity between two orthogonal polarization states and the angle of incidence of the incoming beam. In general, thermal detectors and diode-based trap detectors have been shown to have negligible polarization dependence. The polarization dependence is quantified by measuring the detector response while varying the incoming polarization state and/or angle of incidence.

6.1.5 Thermal Dependence (Type B)

While all detectors will be sensitive to temperature, some may exhibit significant thermal dependence that may contribute to the uncertainty contribution. Diode-based detectors may have significant thermal dependence, which can alter the spectral responsivity of that detector. Thermal detectors may also have a dependence on the ambient temperature, although to a much lesser extent. Temperature variations during the calibration procedure are documented and are used to quantify (bracket) the maximum possible variation of the detector response during the measurement. The temperature dependence of the detector being evaluated, if not thermally stabilized or compensated by some other means, must be characterized and the resultant thermal dependence factored into the uncertainty budget. This characterization requires determination of

the detector response as a function of temperature. An example of such behavior is documented in NIST Special Publication 250-53 [19].

6.1.6 Window Transmittance (Type B)

For a detector where responsivity is determined by methods other than direct substitution, it is necessary to characterize the window transmittance. A method of determining the uncertainty contribution of window transmittance for calorimeters is described in West, Case, Rasmussen and Schmidt [4]. The uncertainty associated with the window transmittance of the standard calorimeters currently used in this service is discussed by T.R. Scott [8].

6.1.7 Electronics (Type B)

Where individual standards utilize discrete electronics that are integral to that detector, the accuracy of these electronics will also contribute to the uncertainty of the measurement. The contributions will vary from detector to detector depending on the electronics, and are accounted for in the individual uncertainties for each detector used.

6.1.8 Inequivalence (Type B)

In the case of electrically calibrated standards, the difference in temperature response between optically delivered power and electrically delivered power (during calibration of the standard) is described as the inequivalence of the detector. As an example, the methods used to determine this value for the isoperibol calorimeter are described by E.G. Johnson [20]. This uncertainty is currently implemented only for measurements using electrically calibrated calorimeters. The uncertainty for the inequivalence of the standard calorimeters used in this service is covered by T.R. Scott [8].

Table 6.1. Example uncertainty budget for calorimeter-based measurements.

Example Uncertainty Summary Table Standard/Detector	Type B	Type A	
	δ_i	S_r	N
Transfer Standard			
Responsivity	0.03 %		
Electronics	0.50 %		
Uniformity	0.14 %		
Temperature Stability	0.02 %		
Polarization Dependence	0.02 %		

6.2 *Measurement System Uncertainties*

The uncertainties for this service are included in each calibration report, and are summarized here. The error budget is summarized below in table 6.2.

6.2.1 Injection Time (Type B)

The evaluation of energy meters and calorimeters requires integration over the entire injection time. Precise control of the injection time is accomplished by use of a computer-controlled shutter. The specified accuracy of the timing card, in combination with the manufacturers published shutter speed, results in an uncertainty contribution of 0.05 % (*see appendix A, A.1*).

6.2.2 Laser Power Drift (Type B)

The variation of laser power during a given measurement can impact the accuracy of the measurement. Most lasers will tend to exhibit some form of power instability over the relatively shorter durations (100 to 300 s) of an individual measurement. The uncertainty contribution of laser power stability to the measurement is quantified by the difference in the average power over the full injection period and the average power measured after the settling time. Because different laser sources will have different drift characteristics, modeling of laser power drift was done to determine an upper bound of 0.50 % contribution to the uncertainty of the measurement (*see appendix A, A.3*).

6.2.3 Aperture Effects

The aperture effect is a function of the beam size and the properties of the detectors being compared, such as the detector area, aperture area, field of view, and spatial uniformity. More generally, it is described as an uncertainty contribution due to differing fields of view between detectors utilized in the measurement. If the detectors being compared have active areas of different size, in principle the detectors being compared do not see the same amount of optical power. The methods used to characterize this effect are described in NIST Special Publication 250-62 [16]. However, the contribution to the overall uncertainty budget is negligible in this measurement service.

6.2.4 Laser Pointing Stability (Type B)

Small drift in the laser pointing (location of the laser beam where it intersects the detector plane) contributes to the calibration uncertainty. Rather than quantify the pointing stability on a case-by-case basis (for each laser wavelength, each laser and optical alignment, each customer, etc.) for each calibration, we define an upper bound for the pointing stability with a Type B uncertainty. The value of this contribution is 0.50 % (*see appendix A, A.2).*

6.2.5 Beamsplitter Ratio (Type A)

The uncertainty of the beamsplitter ratio directly affects the overall uncertainty, and is accounted for by the standard deviation of the beamsplitter ratio measurements, as described in section 3.

6.2.6 Transfer Measurement (Type A)

The accuracy of the direct substitution measurement is quantified by the standard deviation of the transfer-standard calibration factors (see Eqs. 3.4a and 3.4b).

Table 6.2. Example summary of system uncertainties.

Example uncertainty summary table system	Type B	Type A	
	δ_i (%)	S_r	N
System uncertainties			
Inject time	0.05		
Laser power drift	0.50		
Laser pointing stability	0.50		
Beamsplitter ratio		0.11	n
Transfer measurement		0.06	n

7. Quality Control

The Optoelectronic Division measurement services make use of quality assurance practices to ensure the validity of measurement results and their uncertainties. Such practices include:

- Repeated measurements/calibrations compared over many time intervals.
- Comparison of previous results obtained using multiple reference standards if available.
- Routine, periodic internal comparisons of NIST standards that are used in calibrating the DUT.

In the Optoelectronics Division, all calibration, measurement assurance program (MAP), and remote measurement (RM) services maintain check standards and control charts for periodic testing of the measurement service. The procedure for selecting, storing, maintaining, and measuring check standards, control charts, and other practices are be described in the QM-III quality manual.

When available, historic data from previous measurements of a detector shall be placed into the test folder by the Measurement Services Coordinator after the preparation of the calibration report. The Calibration Leader and the Group Leader shall review this data before signing the calibration reports. If a significant variance from previous results is observed, the Group Leader may require another measurement of the check standard and calibration item as a test of measurement system conformance.

8. Summary

The calibration service provides responsivity of laser power and energy meters by direct substitution with an ensemble of reference detectors having a responsivity that is traceable to SI units through the NIST LOCR. The service employs a wide range of laser power and energy levels over a broad spectrum of wavelengths. In this document we have summarized the basic measurement equation, the measurement procedure, and described the quantities that contribute to the relative standard uncertainty.

9. Glossary

Calorimetry:

The measurement of the quantity of heat exchanged. In this service, the calorimeter is used to quantify the amount of thermal energy deposited by a laser source.

Direct Substitution:

Substituting a known standard for a DUT in identical conditions and comparing the measured results to generate a calibration factor that is directly related to the NIST Standard.

DUT:

Device Under Test.

Injection Period:

Period when laser light impinges on the detector(s) in use.

Isoperibol:

The term "isoperibol" refers to a calorimeter in a constant temperature environment.

Laser Power Meter:

A detector that is used to measure average power.

LOCR:

Laser Optimized Cryogenic Radiometer.

Standard:

For this service, a standard is a detector that has been rigorously characterized, and is directly traceable to NIST electrical standards.

Wedge Beamsplitter:

Detectors and power meters are often calibrated by direct comparison to one of these standards, using a slightly wedged beamsplitter made from a high quality optical material appropriate for the wavelength of operation [15] (Fig. 9.) Several distinct beams are generated by the wedged beamsplitter. Their relative magnitude compared to the incident beam can be readily calculated or measured (Fig. 9.1) and the wedge also minimizes problems with coherent reflections. Several orders of magnitude of calibrated attenuation can be achieved in this way.

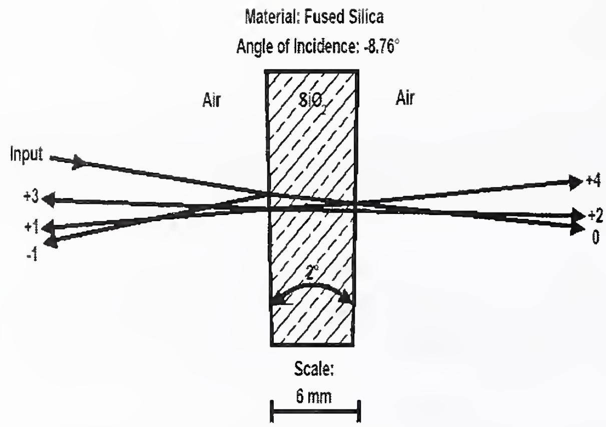

Figure 9.1. Diagram of wedge beamsplitter.

Standard Uncertainty:

The representation of each component contributor to the uncertainty of a measurement result. Typically expressed with the symbol u_i, and equal to the positive square root of the estimated variance u_i^2.

Combined Standard Uncertainty:

The combined standard uncertainty of a measurement result, suggested by the symbol u_c, is taken to represent the estimated standard deviation of the result. It is obtained by combining the individual standard uncertainties u_i (and convariances as appropriate), whether arising from a Type A evaluation or a Type B evaluation. The common method for combining standard deviations, which is summarized in Taylor and Kuyatt [18], is more generally referred to as the "root sum of squares", or RSS.

Expanded Uncertainty:

A measure of uncertainty that defines an interval about the measurement result y within which the value of the measureand Y is confidently believed to lie. The typical representation of expanded uncertainty is the symbol U, and is obtained by multiplying $u_c(y)$ by a coverage factor, typically represented by the symbol k. Thus $U = ku_c(y)$, and it is confidently believed that $y\text{-}U \leq Y \leq y+U$, which is commonly expressed as $Y = y \pm U$. For this service, a coverage factor equal to 2 is used.

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Appendix A. Measurement System Uncertainties

A.1 Injection Time (Type B)

An upper bound was established based on the shutter manufacturer's specifications, which are the following:

Shutter: Window speed = 48 ms
Shutter Controller: ±10 % of shutter speed
Timing Card: 0.05 % timing resolution

The uncertainty for injection time will be dominated by the 0.05 % accuracy specification of the timing card. The shutter speed and controller contribution to the uncertainty, based on a 200 s or greater injection time, has a lesser contribution. That is, (48 ms + 10 % = 53, 53 ms/200 s = 0.02 %). At the shortest expected injection times, the total contribution to the uncertainty of the shutter speed and controller accuracy will be less than 0.02 %.

Thus, the total contribution to the injection time uncertainty, while dominated by the timing card, will include all elements added in quadrature. We will consider this to be a Type B uncertainty with a maximum standard uncertainty of 0.05 %.

A.2 Laser Pointing Stability

The laser pointing stability may be considered spatial drift, or the spatial variation of the location of the laser beam spot on the active area of the detector. The contribution of laser pointing stability is based on the manufacturer's specifications of the lasers in the suite and the corresponding beam path length.

The longest beam path in the laser suite is 18 m. The greatest angular variation is less than 20 µrad. Thus, the angular deviation over that distance is expected to result in a translation of the beam of no more than 500 µm. In most measurement setups, assuming a roughly Gaussian profile, this will result in a loss of beam power of no more than 0.5 % due to beam translation.

This value, 0.5 %, was determined empirically, based on a 500 µm translation of a 2 mm beam (the smallest beam size commonly used) across an aperture set to the extent (see section 5.2.1) of the beam size.

This is considered a worst case scenario, as such; the expected Type B contribution to the uncertainty is set as an upper bound at 0.5 %.

A.3 Laser Power Drift

Noise that is termed drift (or $1/f$ noise) is common to a broad range of physical systems and is observed at low frequencies (having a magnitude inversely proportional to frequency). It is typically not based on a single phenomenon; rather it is observable and identified based on a statistical criterion [A1]. The statement of or drift is given to be consistent with the other types of noise, but distinguishes itself from those that are properly derived as random signals with zero average; that is, the other contributions can be characterized by their autocorrelation function. The $1/f$ noise cannot. In general, $1/f$ noise is inversely proportional to its frequency (the average is not zero). In the case of lasers it may be attributable to a variety of mechanisms, depending on the type of laser (diode laser, gas laser, etc.).

While the design of the measurement service, by use of a monitor detector, can compensate for long-term fluctuations in laser power (individual measurement to measurement). Short-term drift during a single measurement can alter the measurement accuracy. Rather than evaluate and quantify the drift during each calibration episode (for each laser in our ensemble), we state a Type B uncertainty based on manufacturer data and historical data.

The upper bound for this uncertainty is determined from what may be considered a worst-case scenario (that is, large drift over a short period). We model the worst case by the following example:

The model is based on the manufacturer's stability specification that establishes an upper bound for drift. In this case, the largest stability specification is 3.0 %. This 3.0 % stability specification is then applied to the shortest reasonable period during which measurements are commonly performed, which we choose to be 200 s. The relative difference in measured power between the full injection interval/period (over which the calorimeter integrates the signal), and the averaged power signal on the DUT is then calculated. Fig. A1 illustrates this model. The relative difference between the averaged signal (after the settling period) and the integrated signal (over the full injection period) was found to be 0.5 %.

The calculation of the model shown in Eq. (A-1) is represented below.

$$1-\left(\frac{\sum_{DUT}^{end} x}{(end-DUT)} \Bigg/ \frac{\sum_{0}^{end} x}{(end-0)} \right) = 0.5\% \qquad \text{(A-1)}$$

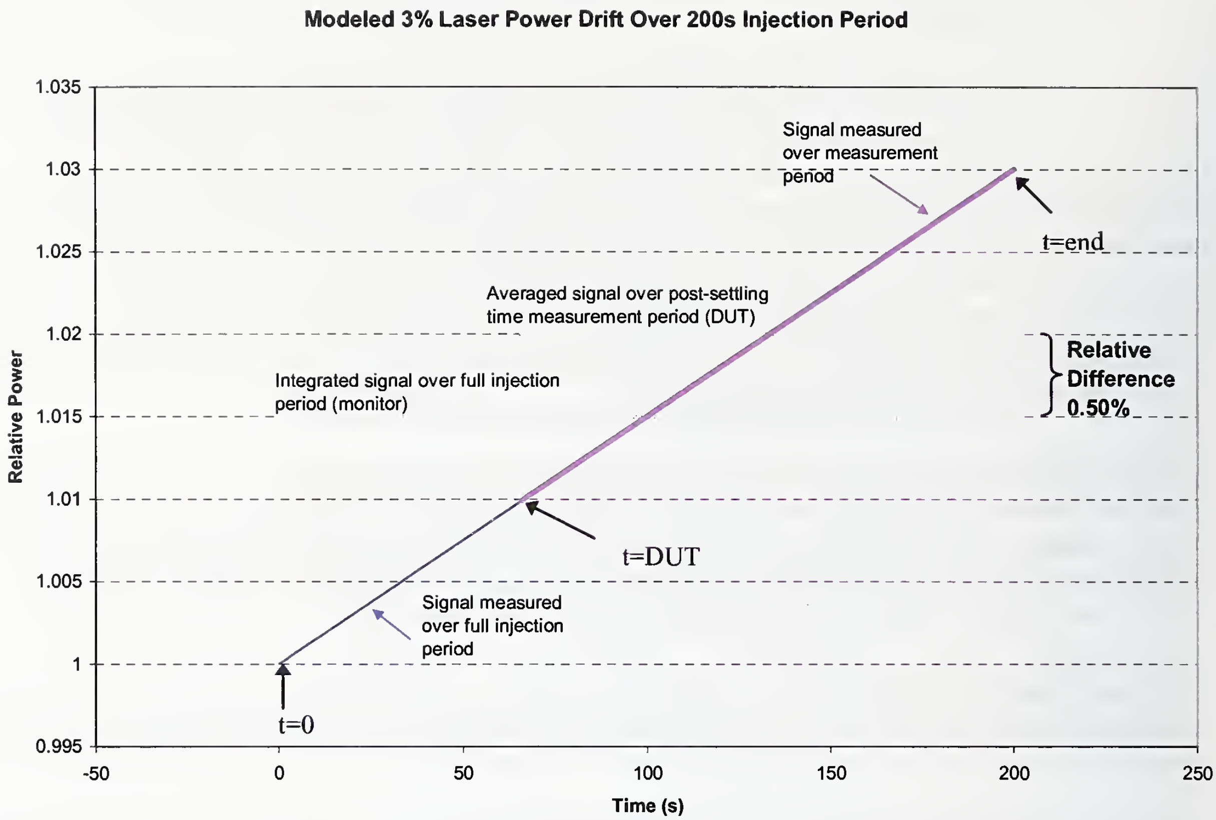

Figure A1. Laser power drift model.

Reference

[A1] D.W. Allan, Should the classical variance be used as a basic measure in standards technology? IEEE Trans. Instrum. Meas. IM-36: 646-654; 1987

Appendix B. Sample Calibration Report

U.S. DEPARTMENT OF COMMERCE
NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY
ELECTRONICS AND ELECTRICAL ENGINEERING LABORATORY
Boulder, Colorado 80305

Report of Calibration (42110CA)

LASER POWER METER
<DUT Mfg., Model, S/N>

Submitted by:

CUSTOMER
<Customer name, address>

Calibration Summary

The laser power meter was compared to NIST standard calorimeters at a wavelength of 1064 nm (Nd:YAG laser). The laser beam had a nominal diameter of 4 mm on the detector surface and the test detector was centered in the incident beam. The power impinging upon the test instrument was measured concurrently by use of a calibrated beamsplitter and a NIST standard calorimeter (see Figure 1). The beamsplitter ratio was calibrated for each data set by use of two NIST standard calorimeters.

Before the measurements began, the test instrument was allowed to reach equilibrium with the laboratory environment. Readings were recorded from the test meter display. The calibration factor was then found by dividing the test instrument reading by the calculated incident power. The ambient temperature during these measurements was approximately 23 ± 1°C.

A summary of the measurements is given in Table I. If the readings of the test instrument are **divided** by the appropriate calibration factor listed in the table, then, on the average, the resulting values will agree with those of the NIST measurement system.

Table I. Calibration results.

Wavelength	Nominal input power	N	Standard deviation	Calibration factor (Rdg/W)	Expanded uncertainty
1064 nm	0.96 W	3	0.03 %	0.9913	±0.86 %

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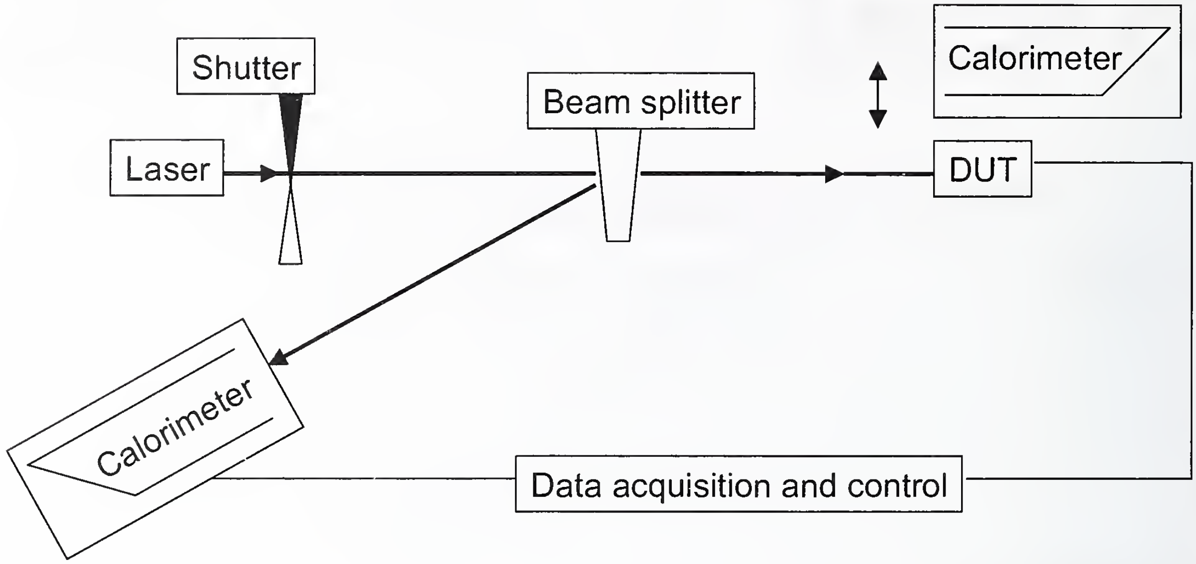

Figure 1. Measurement setup.

Uncertainty Assessment

The uncertainty estimates for the NIST laser energy measurements are assessed following guidelines given in NIST Technical Note 1297, "Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurement Results" by Barry N. Taylor and Chris E. Kuyatt, 1994 Edition. To establish the uncertainty limits, the error sources are separated into (1) Type B errors, whose magnitudes are determined by subjective judgement or other non-statistical method, and (2) Type A errors, whose magnitudes are obtained statistically from a series of measurements.

All the Type B error components are assumed to be independent and have rectangular or uniform distributions (that is, each has an equal probability of being within the region, $\pm \delta_i$, and zero probability of being outside that region). If the distribution is rectangular, the standard uncertainty, σ_s, for each Type B error component is equal to $\delta_i/3^{1/2}$ and the total "standard deviation" is approximated by $(\Sigma\sigma_s^2)^{1/2}$, where the summation is performed over all Type B error components.

The Type A errors are assumed to be independent and normally distributed, and consequently the standard deviation, S_r, for each component is

LASER POWER METER
Detector Model No:
Display Model No:

$$S_r = \sqrt{\frac{\sum x^2 - \frac{(\sum x)^2}{N}}{N-1}} \;,$$

where the x values represent the individual measurements and N is the number of x values used for a particular Type A error component. The standard deviation of the mean is $S_r/N^{1/2}$, and the total standard uncertainty of the mean is $[\Sigma(S_r^2/N)]^{1/2}$, where the summation is carried out for all the Type A error components.

The expanded uncertainty is determined by combining the Type A and Type B "standard uncertainties" in quadrature and multiplying this result by an expansion factor of 2. The expanded uncertainty, U, is then

$$U = 2\sqrt{\sum \sigma_s^2 + \sum \frac{S_r^2}{N}} \;.$$

The values used to calculate the NIST uncertainties are listed in Table II for the power level tested.

The number of decimal places used in reporting the mean value of the calibration factor listed in Table I was determined by expressing the total NIST uncertainty to two significant digits.

Table II. NIST measurement uncertainties at 1064 nm.

Source	Type B	Type A	
	δ_i (%)	S_r (%)	N
Standard calorimeter			
Inequivalence	0.15		
Absorptivity	0.01		
Electronics	0.10	0.10	30
Heater leads	0.01		
Window trans	0.11	0.02	6
Measurements			
Inject time	0.05		
Laser power drift	0.50		
Standard meter ratio	0.50	0.03	6
Transfer meter ratio		0.03	3
Relative expanded uncertainty (k=2)			**0.86 %**

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LASER POWER METER
Detector Model No:
Display Model No:

For the Director,
National Institute of Standards and Technology

Calibrated By:

Marla L. Dowell, Group Leader
Sources, Detectors and Displays Group
Optoelectronics Division

Joshua Hadler, Physicist
Sources, Detectors and Displays Group
Optoelectronics Division

John Lehman, Project Leader
Sources, Detectors and Displays Group
Optoelectronics Division

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